Renewable and Sustainable Energy Reviews 13 (2009) 2070–2078

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Productive use of bioenergy for rural household in ecological fragile area, Panam County, Tibet in China: The case of the residential biogas model

Tingting Feng [a,b], Shengkui Cheng [a,*], Qingwen Min [a], Wei Li [c]

[a] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, A11 DaTun Road, ChaoYang District, Beijing 100101, PR China
[b] Graduate University of the Chinese Academy of Sciences, Beijing 100049, PR China
[c] College of Resources and Environmental Sciences, China Agricultural University, No. 2#, YuanMingYuan West Road, Haidian District, Beijing 100193, PR China

ARTICLE INFO

Article history:
Received 11 May 2008
Accepted 2 February 2009

Keywords:
Productive use of bioenergy
Residential biogas model
Benefit analysis
Tibet

ABSTRACT

Bioenergy is the major domestic energy for rural households in developing countries due to its cheap or easy-getting characteristics. Productive use of bioenergy is an important strategy for rural households to improve not only their income, but also their health, living environment and so on. In Tibet of China, which is rich in cattle dung and firewood as the major energy sources for rural households, the efficiency of energy utilization is just about 10%. In order to improve energy utilization efficiency and the living conditions for rural residents, the Tibet Autonomous Region government introduced residential biogas model (RBM) to local households, which was a comprehensive utilization system of energy integrated with residential biogas digester, vegetable greenhouse and livestock shed. This paper aims to show the productive use of the bioenergy by the RBM, which could be depicted as the feasibility and the benefits on economic, eco-environmental and social aspects of biogas utilization, based on household questionnaires in Panam County. In RBM, biogas digester works as the biomass material supplement loop to transform originally biomass flow from single-direction to recycling-direction. The results indicate that the output of unit biogas digester could replace 1.44 t of firewood, 1.65 t of agricultural residues and 1.75 t of cattle dung, respectively. The net incremental benefit of RBM could reach 5550.72 Yuan in 15 years. The reduced amount of CO_2 emission when substituted by biogas in other agricultural areas and the areas of semi-agricultural and semi-husbandry in Tibet could be $(76.66–79.89) \times 10^4$ t/year and the capability for nitrogen storage could achieve $(0.39–0.99) \times 10^4$ t/year. The amount of cattle dung replaced by biogas could reach 78.29×10^4 t/year; this means that the saved cattle dung, 3.51 t/hm^2, could be reallocated back to cultivated land to improve the soil fertility and to keep the balance of nutrient elements in cultivated land. Biogas utilization reduces the labor opportunity costs of women compared to use of traditional bioenergy sources. It could be concluded that the productive use of bioenergy through RBM in this area has its capability to release the current pressures on biomass sources by adjusting patterns of rural energy consumption, and to improve the conditions of health, environment, economy and energy conservation.

Contents

* Corresponding author. Tel.: +86 10 6488 9797; fax: +86 10 6485 4230.
E-mail address: chengsk_igsnrr@126.com (S. Cheng).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2009.02.001

1. Introduction

Energy, one of the most significant resources in national development, plays pivotal role in the correlation with economic growth and national welfare. In the context of rural development, the conventional characteristics of energy utilization of rural areas focus on promoting income-generating [1–3]. For many rural households, especially in developing countries, traditional bioenergy is still the major domestic energy by direct combustion, which is not only low efficient, but also imposes severe pressures on eco-environment [4–6]. For these countries, productive use of bioenergy is an important strategy for motivating rural sustainable development, which is not merely limited to enhance income, but correlated with improving the living conditions, health, opportunity for education, women's empowerment and so on.

In the workshop of Global Environment Facility (GEF) and UN Food and Agricultural Organization (FAO), scholars gave definition of "productive uses of renewable energy": in the context of providing modern energy services in rural areas, a productive use of energy is one that involves the application of energy derived mainly from renewable resources to create goods and/or services either directly or indirectly for the production of income or value [7]. In this definition, we could focus on the urgencies of shifting ideas from conventional energy to renewable energy (e.g. bioenergy) and the impact of energy services on human development (i.e. education, health, gender equality, etc.), especially for rural residents.

Previous works in South Africa, Ethiopia and India, to name a few, have shown that the vast majority of rural households depend deeply on bioenergy by ways of inefficient utilization, which have negative impacts on environment and rural society development [8–10]. The inefficient combustion has resulted in the over-consuming of bioenergy; the emissions such as carbon monoxide (CO) and particulate matter (PM) have caused respiratory-related illnesses in women, children and infants [11,12]. Time spent in collecting bioenergy also accounts for a major portion of daily labor, especially for women and children, whose time for reading and recreation are deprived [13].

Tibet is located at the southwest part of China with the average elevation more than 4000 m over the sea level. 92% of the land area is under the frigid cold and snowy environment and the structure of ecological vegetation system is simple with short growth time and weak self-adjustment ability. For the outside interference, vegetation growth will be significantly affected, manifesting as biomass reduction, pest intensification, etc. Once vegetation on the steep slopes is damaged, erosion of the surface soil will be accelerated. Grassland degradation of Tibet was 11.43×10^6 hm^2 according to the survey data (1988–1990), accounting for 17.2% of the total available pasture area. Tibet is full of potential resources of renewable energy, such as solar, wind, water and geothermal power [14]. However, the widespread utilization of aforementioned renewable energy is restricted due to cost, scattered location of the rural household and other technological and/or economic limits. Therefore, for a long time the local residents have been selecting easily accessible biomass, such as cattle dung, firewood and agricultural residues, to meet their domestic energy demands [15]. Until now, bioenergy accounts for 92% or more of their total energy consumption [16] and in the near future, bioenergy could still be the main energy for Tibetan rural households. Recently, with the increasing pressures of population, these Tibetan rural residents have to seek more biomass from already-fragile environment. It results in conflicts among domestic fuel, animal fodder and organic fertilizer (3F) [17]; it also intensifies the disturbance to ecological system.

In order to improve the efficiency of energy utilization of rural households and to resolve the conflicts between bioenergy consumption and environment protection, the residential biogas model (RBM), which is a comprehensive energy utilization system integrated with residential biogas digester, vegetable greenhouse and livestock shed, was tested in Tibet Autonomous Region in 2003. This model was firstly used in the northeast part of China to improve the energy utilization efficiency in rural households, and because of its high feasibility for releasing conflicts between energy combustion and environment conservation, this model was popularized and modified under various types of climatic conditions across China [27]. For Tibet, the differences concerning meteorological and agricultural background compared to other parts of China are significant; the ecosystem is more fragile than the original areas where the RBM was firstly developed. From this point of view, the feasibility and benefits analysis of RMB should be taken firstly for further extension to the complete agricultural areas and/or the areas of semi-agricultural and semi-husbandry in Tibet. So we planned a structural questionnaires and interviews for local rural residents and officials in Panam County of Shigatse Prefecture. The major aims of this paper are:

- to distinguish the current energy utilization pattern of rural households in Panam County;
- to analyze the characteristics and functions of the RBM in adjusting patterns of rural energy consumption;
- to investigate the ecological, economic and social benefits as the indicators of productive use of bioenergy, in order to show to what extent the biogas could substitute the traditional bioenergy and its alternating efficiencies.

2. Study area

Panam County locates in the basin of middle reaches of Nianchu River, tributary of Yalutsangpu River, southwest of Tibet. The average altitude is 3950 m, average temperature is 7.6 °C, and average rainfall is 328.7 mm, all of which are typical semi-arid monsoon climate characteristics in temperate plateau region. The area of study region is 2759 km^2, and the area of cultivated land and natural pasture land is 8183.54 hm^2 and 18.21×10^4 hm^2, respectively. This area is the agricultural zones of Tibet with 22.05 capita/km^2 of population density, which is much higher than 2.23 capita/km^2 of the average level all over the whole Tibet.

In 2006, the output ratio among primary sector (agricultural and husbandry products), secondary sector (industrial products) and tertiary sector is 40.98:15.53:43.49, showing primary and tertiary sector is the predominant producing sector in study area. Panam County is one of the grain base counties in Tibet, and its main crop products are Tibetan barley, spring wheat, rape and vegetables. Vegetable production has been developed greatly since vegetable greenhouses and non-governmental organizations are constructed, such as Peasant Vegetable Planting Association. Yaks, goats and pigs are the major kinds of domestic animals in the local rural households.

The natural ecosystem of Panam County has been disturbed by human beings for a long time, because the location of the county is in the cradle of Tibet culture and this area is the traditional residential area for generations. Due to lack of commercial energy, the major domestic energy is cattle dung, firewood and crop residues. Under the pressures of human activities seeking for traditional bioenergy, the ecosystem has been greatly altered, especially for the topsoil characteristics and vegetation degradation by means of collecting cattle dung away from pastureland and fallen shrubs in moisture-rich location [18–20]. For instance, the soil organic matter, Nitrogen and phosphorus contents in this area are 5.50–24.80 g/kg, 0.20–0.70 g/kg and 0.32–0.50 g/kg, respectively, which are in the lowest level throughout Tibet [17]. Considering the low productivity of land, the amount of vegetation collected for fuel and for fodder is limited and the conflicts are intensified with the increasing demands of energy.

In order to solve the conflicts among fuel, fodder and fertilizer (3F) mentioned above, the RBM project with livestock feeding, biogas production and vegetable planting was constructed and tested in Panam County since 2004. This project aimed to release the tense competition among 3F, and organized a harmonious way to balance the development of rural society and protection of eco-environment. The following sections of this paper were based on the questionnaires and interviews held in Panam County.

3. Material and methods

3.1. Material

In our research, data concerning daily energy utilization, such as ways of energy consumption, time spent on cooking, heating, boiling and collecting, and detailed questions about households' health, welfare, costs, benefits, living standards, were collected by questionnaire process from farmers/peasants. In August and November 2007, due to scattered rural households' living sites, we organized structured interviews for only 60 rural households in the study area. Information on energy-environmental problems of the whole study area was obtained through interviewing on officials and scholars of Panam County Science and Technology Bureau. Data about climate, soil, socio-economic development, land use, financing conditions, etc. are selected from yearbooks and other statistical information [21].

3.2. Methods

In this study, we constructed a holistic approach for productive use of bioenergy of RBM integration of structural–functional analysis, economic benefit calculation and socio-ecological effect evaluation. This integrated method reflects the feasibility of RBM in study area with the structural analysis of traditional bioenergy utilization and the functional analysis of traditional bioenergy utilization compared with RBM. This method also reflects the efficiency for economic benefits, environmental conservation and living standard improvement. The structural analysis of traditional bioenergy utilization is based on questionnaires and data from yearbooks in study area. The functional analysis of traditional bioenergy utilization and RBM is based on material and energy flows, a qualitative approach. In this section, we focus on the methods on how to calculate the economic, ecological and social benefits.

3.2.1. Economic benefit calculation

This paper introduces internal rate of return (IRR) to evaluate the investment efficiency of RBM to show the economic benefits. IRR is the discount rate when net present value equals to 0 or benefit–cost ratio equals to 1; IRR also involves the opportunity cost of the investment. If IRR equals to the discount rate of opportunity cost of the capital, the project could achieve the profit level and it can be carried out. In our study, the investor of RBM project is the government, so the basic discount rate was selected to be 10% that was higher than the lending rate of bank, according to social capital discount rate. The calculation equation is as followed:

$$\mathrm{IRR} = i_1 + \frac{|\mathrm{NPV}_1|}{|\mathrm{NPV}_1| + |\mathrm{NPV}_2|} \times (i_2 - i_1) \tag{1}$$

In Eq. (1), IRR is financial internal rate of return; NPV is net present value, and NPV_1 is the lowest positive value which is most close to 0, corresponding to lower discount rate i_1; NPV_2 is the most maximum negative which is most close to 0, corresponding to higher discount rate i_2.

3.2.2. Ecological benefit calculation

The amount of CO_2 emission reduction and nitrogen preservation after RBM project implementation was used to describe the ecological benefits of RBM.

The CO_2 emission reduction of biogas could be regarded as the difference between biogas burning and traditional bioenergy direct combusting. According to three different energy-replacing patterns (biogas–firewood, biogas–residue and biogas–dung), the Eqs. (2)–(4) were formulated. The parameters were based on Wang [22].

$$\delta C_i = C_{\mathrm{BM},i} - C_{\mathrm{BG}} \tag{2}$$

δC_i represents the CO_2 emission reduction when using biogas to replace the i kind of traditional bioenergy (t); $C_{\mathrm{BM},i}$ is the CO_2 emission of the i kind of traditional bioenergy burning (t); C_{BG} is the CO_2 emission of biogas burning (t); parameter i refers to types of traditional bioenergy: firewood, cattle dung and agricultural residues.

$$C_{\mathrm{BM},i} = B_{M,i} \times C_{\mathrm{cont},i} \times O_{\mathrm{frac},i} \times \frac{44}{12} \tag{3}$$

$C_{\mathrm{BM},i}$ is the CO_2 emission of bioenergy (t); $B_{M,i}$ is the amount of bioenergy consumption (t); $C_{\mathrm{cont},i}$ is the carbon coefficient of bioenergy containing (%); $O_{\mathrm{frac},i}$ is the oxidation efficiency of bioenergy when it is burnt (%). Table 1 shows detailed coefficients.

$$C_{\mathrm{BG}} = B_G \times R \times \eta \times \frac{44}{12} \tag{4}$$

C_{BG} is the CO_2 emission of biogas burning (t); B_G is the amount of biogas consumption (10^4 m^3); R is the calorie of per unit biogas release (0.209 TJ/10^4 m^3); η is the CO_2 emission coefficient of biogas (15.3 t/TJ).

The contribution of nitrogen conservation after biogas implementation is calculated as follows:

$$N_{\mathrm{BG},i} = M_{\mathrm{BG},i} \times \lambda \tag{5}$$

$N_{\mathrm{BG},i}$ is nitrogen conservation when i kind of traditional bioenergy replaced by biogas (t); $M_{\mathrm{BG},i}$ is the amount of traditional bioenergy which can be replaced by biogas (t); λ is the nitrogen ratio of traditional bioenergy (Table 1).

Table 1
Basic coefficients of traditional bioenergy (%).

Bioenergy type	Carbon emission coefficient	Oxidation efficiency	Nitrogen ratio
Firewood	45	87	0.63
Residue	40	85	0.53
Cattle dung	39	85	1.27

Source: ref. [23].

3.2.3. Social benefit calculation

We used the women's time opportunity cost of utilizing traditional bioenergy as the indicator of social benefits of RBM. The Eqs. (6) and (7) were constructed according to Kanagawa and Nakata [13]:

$$S_B = M \times W_{\mathrm{BOP}} \tag{6}$$

S_B is the benefit of RBM project (Yuan); M is the amount of traditional bioenergy that can be replaced by biogas (kgce); W_{BOP} is the women's time opportunity cost when they use traditional bioenergy (Yuan/kgce).

$$W_{\mathrm{BOP}} = \frac{W_{\mathrm{OP}}}{E} \times T_B \tag{7}$$

W_{OP} is women's time opportunity cost (Yuan/h); E is the average energy consumption of rural household per day (kgce/day); T_B is the extra time consuming when women use traditional bioenergy (h/day), including the time of bioenergy collecting and the prolonged time cooking with traditional bioenergy.

4. Results

4.1. Traditional bioenergy consumption structure of local rural households

In Panam County, energy types include cattle dung, crop residues, firewood, electricity, solar stove and little fossil energy. Energy utilization sequences in daily lives for rural households could be illustrated in Table 2. Cattle dung and firewood have the priority for heating, then for cooking and boiling Tibetan butter tea, and lastly for fertilizer. Crop residues are mainly used as livestock fodder, and then used for cooking. Electricity is used for lighting and electrical appliances. Solar energy is only used for boiling water. Fossil energy is mainly used for agricultural machinery, and natural gas is used for cooking. It illustrates that traditional bioenergy for cooking can be replaced by fossil and solar energy with just small percentage; energy for heating, lighting, electrical appliances and agricultural machinery cannot be replaced by other types of energy.

Table 2
Energy utilization sequences of rural households in Panam County.

Utilization	Dung	Firewood	Residue	Electricity	Solar	Fossil
Cooking	2	2	2	–	–	2
Heating water	4	3	3	–	1	–
Heating space	1	1	–	–	–	–
Lighting	–	–	–	1	–	–
Electrical appliance	–	–	–	2	–	–
Agricultural machinery	–	–	–	–	–	1
Tibet butter tea	3	4	–	3	–	–
Livestock fodder	–	–	1	–	–	–
Fertilizer	5	–	–	–	–	–

Notes: Numbers 1–5 stand for the declining priority sequences of energy utilization; 1 is for the most importance and 5 is for the least importance. Character "–" stands for energy, which is not used in this way.

In terms of energy types of consumption, traditional bioenergy (i.e. cattle dung, firewood and agricultural residues) is still the main domestic energy for rural households and accounts for 94.19% of the total energy consumption. Cattle dung, firewood and residues hold the percentage of 51.76%, 30.55% and 11.88%, respectively. Solar energy, fossil energy and electricity account for 2.78%, 2.07% and 0.97% of whole energy consumption, respectively.

In terms of the energy consumption pattern, heating and cooking are the primary aspects of energy utilization. Energy for space heating accounts for 50.56%; cooking and boiling water are altogether in the proportion of 38.85%. Energy for Tibetan butter tea accounts for 7.65%, and energy for agricultural machinery, lighting and electrical appliance is 2.94% in all.

To sum up, domestic energy (for cooking and heating) is the main aspect of rural energy consumption, accounting for almost 94% of the whole energy consumption. The ratio of energy consumption for space heating is as high as 50%. It is the major part of traditional bioenergy consumption, such as cattle dung and firewood. More detailed information could be found in Table 3.

4.2. Characteristics of material/energy flows of traditional bioenergy utilization system

In Panam County, traditional bioenergy (cattle dung, firewood and agricultural residues) is mainly for direct combustion. The characteristic of material/energy flow is as follows (Fig. 1): the material and energy held in biomass, generating from local ecosystem, are transformed to energy of fodder and/or agricultural residues, which can be directly combusted or transformed into certain forms of energy existing in livestock.

The energy and material flows in traditional bioenergy utilization system are single-oriented with the only goal for combustion, ignoring the feedback and supplement back to the ecosystem (e.g. land), which is the key factor resulting in energy-environment problems.

The conventional way of bioenergy utilization has significant impacts on rural households' living standard levels, as Fig. 2 depicts. Collecting a large number of firewood and cattle dung not

Table 3
Energy structure of rural household and utilization distribution in Panam County (kgce/year).

Application	Cattle dung	Firewood	Residue	Electricity	Solar stove	Fossil	Total
Cooking	515.75	416.83	547.5	–	–	1.71	1481.79
Heating water	343.83	208.05	182.5	–	170.96	–	905.34
Heating space	2062.98	1043.90	–	–	–	–	3106.88
Lighting	–	–	–	26.54	–	–	26.54
Electricity appliance	–	–	–	28.76	–	–	28.76
Agricultural machinery	–	–	–	–	–	125.31	125.31
Tibet butter tea	257.87	208.42	–	4.04	–	–	470.33
Total	3180.43	1877.20	730.00	59.34	170.96	127.02	6144.95

Notes: Based on interviews on local rural residents.

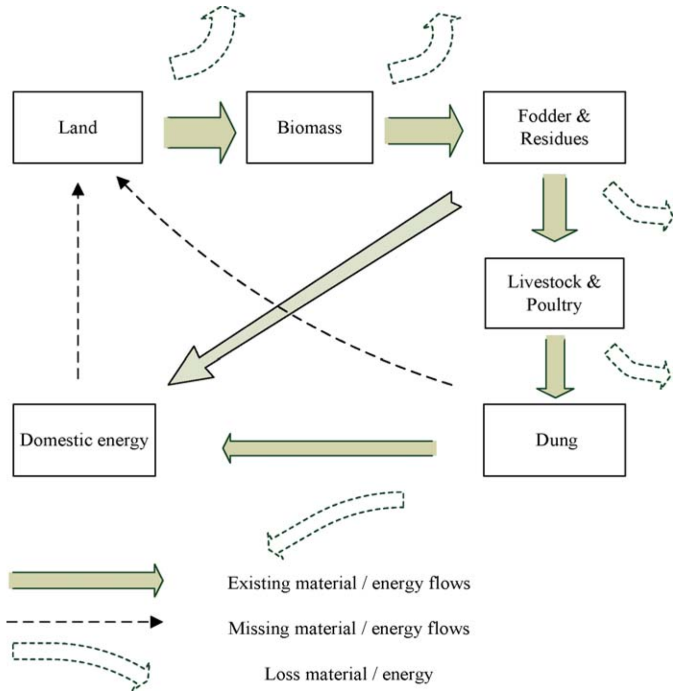

Fig. 1. Material and energy flows of traditional bioenergy utilization system.

only induces eco-environment decay, such as deforestation and land degradation, but also occupies the time of household's labors, which is generally done by housewives and/or children. The biomass is combusted directly and the efficiency is nearly 10% [14]. CO_2 emissions and other indoor air pollutants result in the poor health of local rural households, leading to the diseases of eyes and respiratory organs. Because a large amount of cattle dung is used as fuel, the alternative function as fertilizer is thus limited; this may lower the topsoil fertility and result in less land productivity than leaving cattle dung on pastureland as fertilizer. What is more, this phenomenon would lead to poverty and low level of socio-economic development, which may be the vicious circulation.

4.3. Characteristics of material/energy flows of RBM system

In order to achieve the sustainable development of the energy–environment system, RBM has been testified in Panam County since 2004, adding material supplement loop to tradition bioenergy utilization system. The RBM can transform biomass combustion from single-direction flow to recycling-direction flow (Fig. 3). The supplement loop works as the transition controller, which can compensate necessary energy and material to ecosystem where biomass is generated. For one thing, this loop can enhance the relationship between material utilization of one stage and the original ecosystem for the next stage, and guarantee

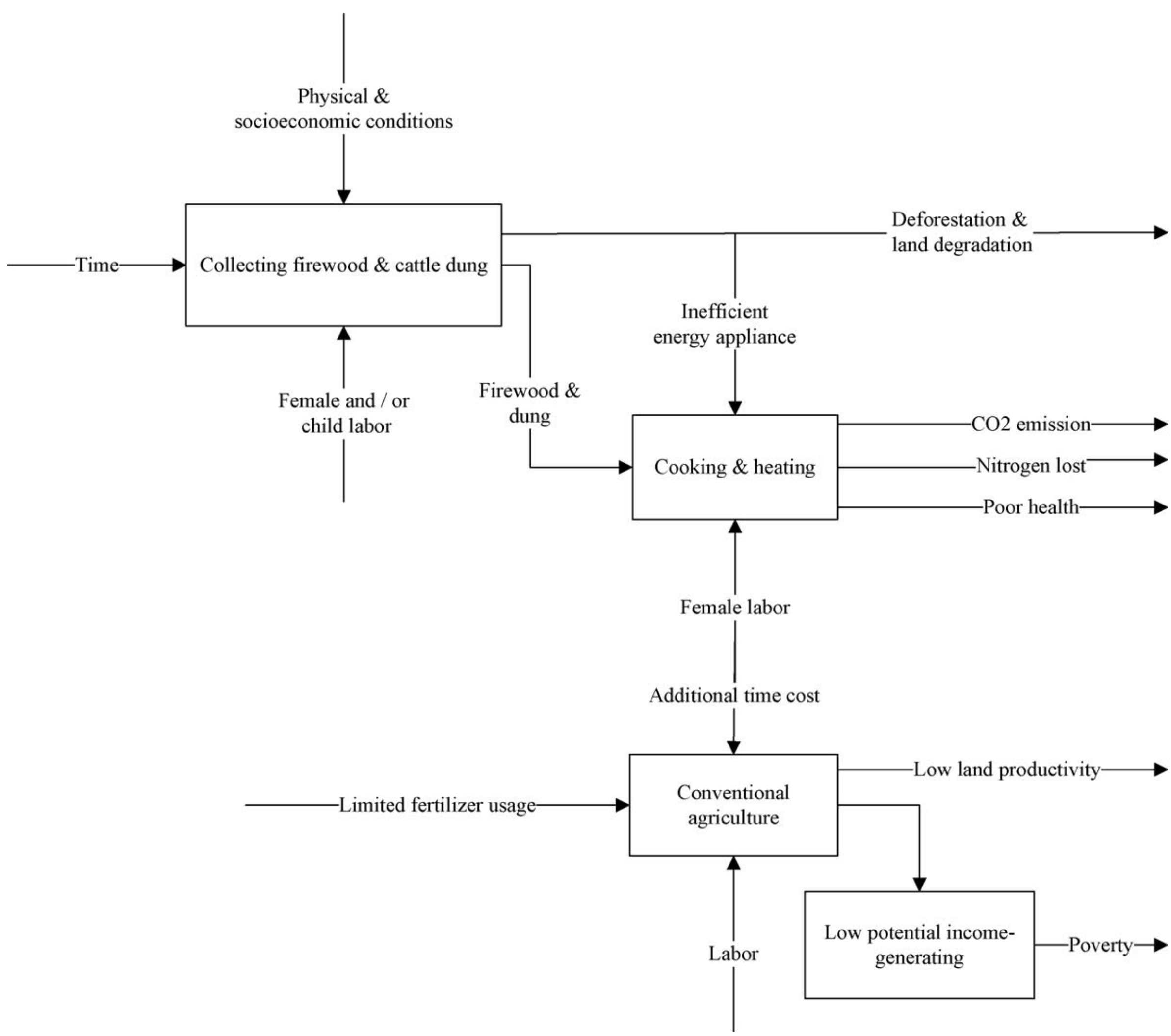

Fig. 2. Traditional bioenergy utilization system and its ecological and socio-economic effects. Revised based on Srinivasan S (2008) [23].

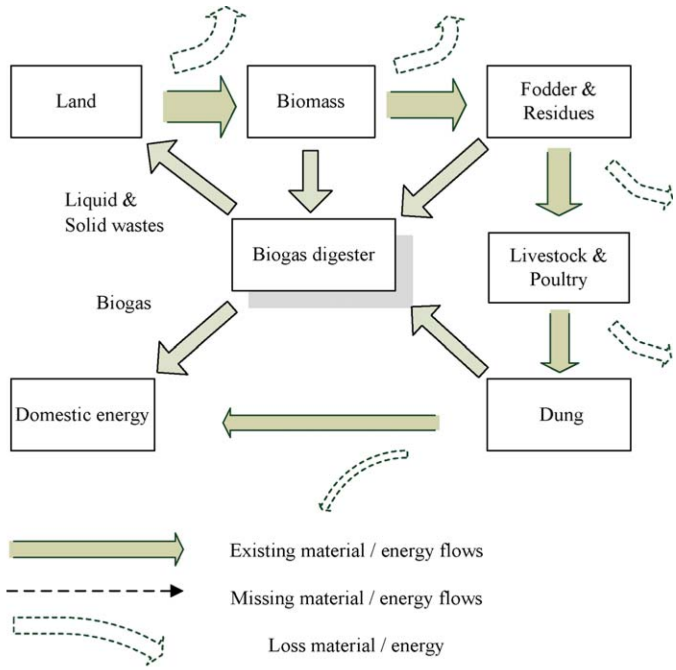

Fig. 3. Material and energy flows of RBM.

the material–energy efficiency and economic output. For another, biogas system works as a trigger, which can regulate the material and energy balance in the whole energy system. In terms of biophysical system, biogas liquid and solid wastes are the elements for land fertility maintenance, which is the negative feedback to keep the material balance in ecosystem. For households' energy system, biogas inputs are a positive feedback to maintain rural household living-producing system.

The ecological and socio-economic effects of RBM can be illustrated by Fig. 4. For RBM, the biogas digester feedstock, is mainly selected from human excreta, cattle dung and residues; the vegetable greenhouse is used to improve the digesting pool's working temperature to maintain stable biogas production and also guarantee livestock spending winter safely. One of the byproducts, CO_2 from biogas burning, cattle respiration and organic matter decomposition can enhance photosynthesis of vegetables. Moreover, other byproducts (e.g. residual dreg and liquor) are fermented in the digester pool, and could be used as organic manure for the vegetables and as livestock feedstuff. In this way, space heating, biogas steady production, manure accumulation, vegetable planting and livestock feeding are all accomplished with circulation step by step. In this regard, RBM's utilization in rural household can enhance the biomass use efficiency and improve the land productivity and rural household living standard, including saving cattle dung for fertilizer usage, decreasing indoor air pollution, improving health condition, releasing the burden of housewives and increasing the time for economic activities or education.

4.4. Benefits analysis of the RBM project from rural household's perspective

4.4.1. Economic benefit

The RBM tested for rural households aforementioned was supported by the Panam County government, and rural households were only required to maintain the normal action of the testing centre. Based on thermal transformation efficiency, the thermal energy of 1 m^3 biogas is equal to 5.00 kg of that of firewood, and the production of 10 m^3 biogas can save 360.13 Yuan (unit of

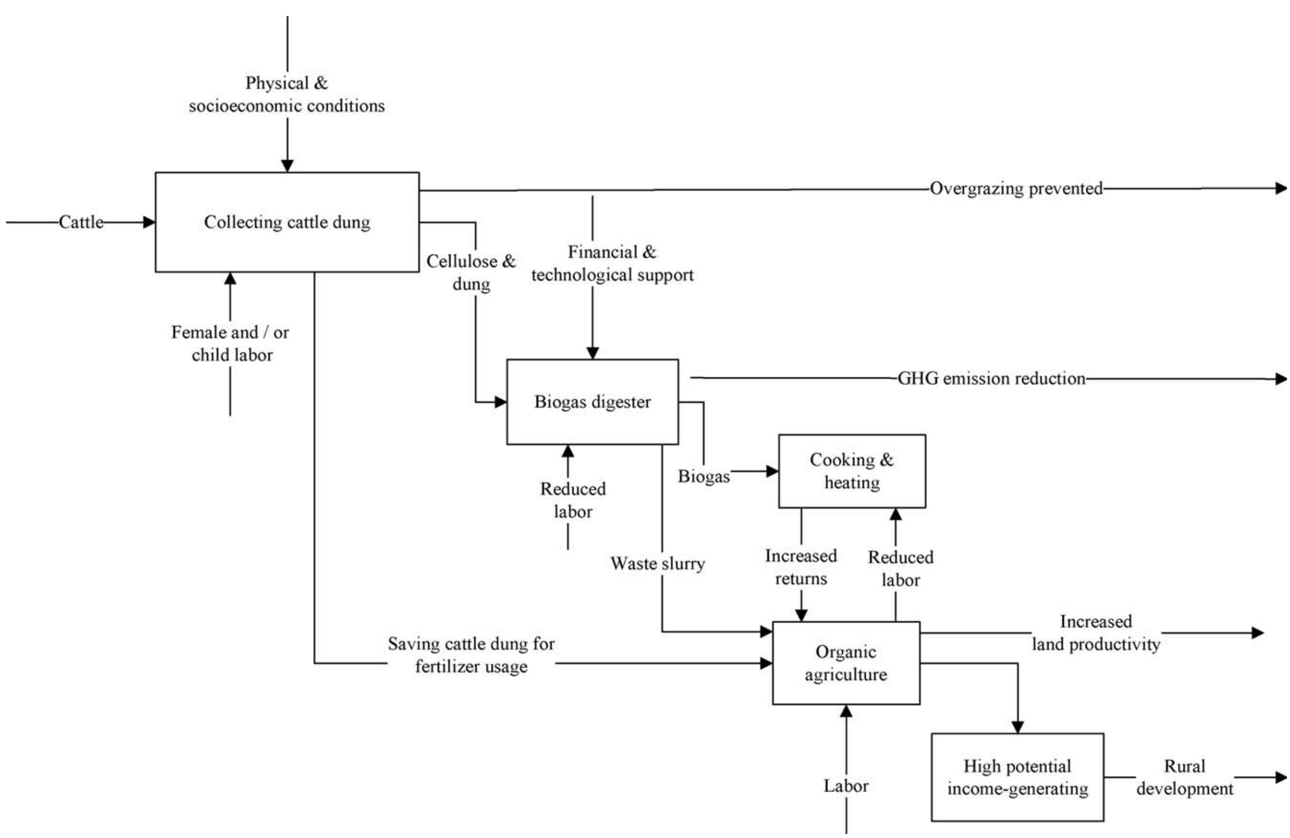

Fig. 4. RBM and its ecological and socio-economic effects. Revised based on Srinivasan S (2008) [23].

Table 4
Costs and benefits of the RBM project.

Costs–benefits	Amount
Total costs	
Solar–biogas digester[a] (Yuan/unit)	4300.00
Facility[b] (Yuan/unit)	300.00
Maintenance per year[c] (Yuan/unit)	50.00
Power per year[d] (Yuan/unit)	230.00
Changing pipes every 8 years[e] (Yuan/unit)	50.00
Total economic benefits	
Biogas production per household per year[f] (m^3/unit)	288.00
Benefits of biogas replacing firewood per year[g] (Yuan/unit)	360.13
Incremental net benefit by vegetable production per year[h] (Yuan/unit)	1000.00
Incremental net benefit of biogas-energy model project (15 years) (Yuan/unit)	5550.72
Internal rate of return (IRR) (%)	36.69

Notes: superscript letters a–e, h are collected by Panam County Science and Technology Bureau; f is calculated based on the data of households' questionnaire; f is calculated based on the fact that biogas can be used for 1 h/day from April to June and 3 h/day from July to September; a is based on the fact that the prices are consisted of constructions of solar greenhouse (35 m^2), rooms for livestock (20 m^2) and cost of maintenance of biogas pool (10 m^3); the service life of a biogas pool is 15 years; g is based on the fact that price of firewood is 25 Yuan/100 kg according to Liu [24].

Chinese currency), used to purchase firewood per year. The biogas slurry and residues can be used as fertilizer for uncontaminated vegetable production, and 35 m^2 vegetable greenhouses can achieve incremental net benefits up to 1000.00 Yuan/year. These two items account for 54.96% of net income per capita. If the service life of a biogas pool is deemed as 15 years, rural households can get incremental net benefit as much as 5550.72 Yuan. Using Eq. (1), IRR can be calculated as 36.69%, which is much higher than 10% (the basic discount rate based on the level of loan interest rate of bank) we selected before. Table 4 shows the detailed information.

4.4.2. Ecological benefit

The productivity of each residential biogas digester is 288.00 m^3/year, which can replace 1.44 t of firewood, 1.65 t of agricultural residues and 1.75 t of cattle dung, respectively, and account for 43.82%, 112.68%, 25.86% of the three items rural household consume per year. In addition, the efficiencies of reduction of CO_2 emissions substitution of firewood, residues and cattle dung are 1.73 t, 1.71 t and 1.79 t, respectively. The efficiencies of reduction of N loss by substitution of firewood, residues and cattle dung are 9.08 kg, 8.72 kg and 22.18 kg, respectively. Table 5 shows the detailed information.

According to Wei et al. [16], the amount of cattle dung which is put into cultivated land as fertilizer could reach 2.91 t/hm^2/year, and at least 6.01 t/hm^2 of cattle dung is required to keep the energy flow balance of cultivated land. Therefore, it needs at least additional input of 3.10 t/hm^2 of cattle dung per year to keep the balance of material flows in ecosystem of cultivated land. If we promote the RBM in Panam County to other agricultural areas and

Table 6
Social benefits of the RBM project.

Types	Amount
Women's contribution to household's income (Yuan/year)	9181.66
Women's opportunity cost (Yuan/h)	3.14
Women's opportunity cost with fuel wood (Yuan/kgce)	0.75
Women's opportunity cost with fuel wood per year (Yuan/year)	4323.88

areas of semi-agricultural and semi-husbandry, the amount of cattle dung replaced by biogas would reach 78.29×10^4 t. This assumption equals to the fact that cattle dung allocated in per hectare of cultivated land can reach 3.51 t/hm^2 and can keep the balance of nutrient elements for cultivated land. Additionally, biogas can reduce the emission of CO_2 $(76.66–79.89) \times 10^4$ t, and the nitrogen losses can be reduced $(0.39–0.99) \times 10^4$ t. The efficiency of firewood replacement by biogas in this basin can reach 27.68×10^4 t that equals to 5.03×10^4 hm^2 net primary production of alpine shrub [25].

4.4.3. Social benefit

The evaluation of social benefits was based on calculation of women's opportunity cost. Rural housewives should devote their time not only to household economic activities, but also to housework, including cooking, collecting dung, firewood and residues, etc. Based on the questionnaire results, housewives spent 1.5 h on collecting bioenergy, and extra 2.5 h on cooking with traditional bioenergy. In the investigation process, we have noticed that housewives work for 8 h/day annually. From this point of view, they may create economic value accounting for 53% of household income [26]. Table 6 shows the women's opportunity cost compared with that of traditional bioenergy.

Women's opportunity cost with traditional bioenergy per year accounts for 47.09% of women's contribution to household's income. Due to the increase in household's income, the opportunity cost of women also rises up [13], and the social benefits are even outstanding. Additionally, women and children have more time for recreation when traditional bioenergy has replaced by biogas. And biogas is good for household's health by reducing indoor air pollution [27].

5. Discussion and conclusions

Globally, the shortage of traditional fossil energy (commercial energy), the environmental damages resulting from energy consumption, and the sustainable development altogether compel us to pay more attention to renewable energy utilization and impact analysis. Regionally, the strategic importance of Tibet for China and even the East Asia, the conservation of religious and conventional living styles and surroundings, the promotion of economic development and the sustainable living conditions also call for specific regulations on how to enhance and guarantee the productive use of bioenergy, and how to promote multi-level and recycled bioenergy utilization in Tibetan rural society. This is the

Table 5
Ecological benefits of different energy-replacing patterns.

Scheme	Equal to (t)			Reduction of CO_2 emission (t)			Reduction of N losses (kg)		
	Firewood	Residue	Dung	Firewood	Residue	Dung	Firewood	Residue	Dung
Replacing firewood	1.44	–	–	1.73	–	–	9.08	–	–
Replacing residue	–	1.65	–	–	1.71	–	–	8.72	–
Replacing dung	–	–	1.75	–	–	1.79	–	–	22.18

Notes: These benefits are based on the replacing capability of 288 m^3 biogas utilization.

vital importance to solve the inconsistencies between rural energy demands and pressures from environment conservation, i.e. the conflicts among domestic fuel, animal fodder and land fertilizer. In this paper, we selected the indicators from economic, ecological and social perspectives to show the productive use of bioenergy utilization. Then, we organized questionnaires for both rural household residents and interviews on officials in local government, and took a county-level investigation to reflect the replacing efficiencies when these indicators were linked to RBM project held in Panam County of Shigatse Prefecture.

The paper analyzed (1) the current rural energy utilization pattern (especially the bioenergy); (2) the characteristics of traditional energy and the function and routine of RBM tested in Panam County; and (3) the benefits of RBM from economic, ecological and social perspectives. The results indicate that:

- traditional bioenergy is the major kind of energy for domestic use (cooking and heating), which accounts for 94.19% (cattle dung 51.76%, firewood 30.55% and residues 11.88%) of the total household energy consumption, and space heating is the main way for bioenergy consumption with the ratio 66.37% of total traditional bioenergy consumption which is mainly supported by cattle dung as well as firewood and little energy substitution could be found;
- the rate of energy consumption which can be substituted by biogas for firewood, agricultural residues and cattle dung is 43.82%, 112.68% and 25.86%, respectively; the reduced amount of CO_2 emission when replaced by biogas is 1.73 t/year for firewood, 1.71 t/year for residue and 1.79 t/year for dung; the capabilities for nitrogen reservation when replaced by biogas is 9.08 kg/year for firewood, 8.72 kg/year for residue and 22.18 kg/year for dung;
- the reduced amount of CO_2 emissions and the capability for nitrogen storage, when traditional bioenergy substituted by biogas in the completely agricultural areas and the areas of semi-agricultural and semi-husbandry in Tibet, are $(76.66–79.89) \times 10^4$ t/year and $(0.39–0.99) \times 10^4$ t/year. The saved cattle dung, 3.51 t/hm^2, could be re-allocated back to the completely cultivated land in Tibet to improve the soil fertility and to keep the balance of nutrient elements.
- the net incremental benefit of RBM could reach 5550.72 Yuan in 15 years and biogas utilization could save 360.13 Yuan payout per year; biogas utilization also saves the opportunity cost of housewives who are using traditional bioenergy.

Our benefit analysis results were based on RBM project, which was tested for the replacing efficiency for cattle dung, firewood and other traditional bioenergy. However, climatic conditions differ greatly across Tibet and hence the biogas production and even the replacing efficiency and benefits could be different from our study area to other parts of Tibetan rural areas. From this point of view, this paper gave definite explanations on rural energy utilization status quo, functions of RBM project and benefits of traditional energy substitution of this project, and provided rough estimation on the replacing efficiency of biogas at the level of Tibet autonomous region. Although the data were limited, we placed the data from interviews up scaling to the whole Tibet agricultural areas and semi-agricultural and semi-husbandry areas, and made an extensive assumption: the basic information of our study area could be recognized to be the same as the whole Tibet agricultural areas and semi-agricultural and semi-husbandry areas, where no heterogeneity occurs. The potential of biogas substitution for traditional bioenergy can be improved if the local households can skillfully maintain biogas system according to the season and the temperature. Further efforts concerning comparison with other types of renewable energy and researches on energy utilization of pasture areas should be organized for refining our results.

Acknowledgements

The authors wish to acknowledge Dr. Kui Ma from Washington, DC in USA and Miss Rui Zhao from Northeastern University of China for their dedicative and enthusiastic revision and suggestions to this paper. We all appreciate the suggestions from Master Wei Sun in Institute of Geographic Sciences and Natural Resources Research, Zhen La in the Panam County Science and Technology Bureau, Caichang Xu in the Shigatse Prefecture Science and Technology Bureau and Zhiyong Gao in the Institute of Tibetan Science and Technology Information. We also thank the management authorities and staff of Tibet Autonomous Region Science and Technology Department and for their helps during the questionnaires and interviews in Panam County.

References

[1] ChowdaGowda M, Raghavan GSV, Ranganna B. Rural waste management in a south Indian village—a case study. Bioresour Technol 1995;53(2):157–64.
[2] Prasertsan S, Sajjakulnukit B. Biomass and biogas energy in Thailand: potential, opportunity and barriers. Renew Energy 2006;31(5):599–610.
[3] Mirza UK, Ahmad N, Majeed T. An overview of biomass energy utilization in Pakistan. Renew Sustain Energy Rev 2008;12(7):1988–96.
[4] Dendukuri G, Mittal JP. Household energy needs of a village in the Rayalaseema area of Andhra Pradesh, India. Energy Convers Manage 1993;12:1273–86.
[5] Wijayatunga PDC, Attalage RA. Analysis of household cooking energy demand and its environmental impact in Sri Lanka. Energy Convers Manage 2002;43(16):2213–23.
[6] Liu G, Lucas M, Shen L. Rural household energy consumption and its impacts on eco-environment in Tibet: taking Taktse County as an example. Renew Sustain Energy Rev 2008;12(7):1890–908.
[7] FAO White Report. GEF-FAO workshop on productive uses of renewable energy: experience, strategies, and project development. Workshop Synth. Rep. Rome, Italy: FAO; 2002.
[8] Madubansi M, Shackleton CM. Changes in fuelwood use and selection following electrification in the Bushbuckridge lowveld, South Africa. J Environ Manage 2007;83(4):416–26.
[9] Wolde-Ghiorgis W. Renewable energy for rural development in Ethiopia: the case for new energy policies and institutional reform. Energy Policy 2002;30(11–12):1095–105.
[10] Ramachandra TV, Subramanian DK, Joshi NV, Gunaga SV, Harikantra RB. Domestic energy consumption patterns in Uttara Kannada District, Karnataka State, India. Energy Convers Manage 2000;41(8):775–831.
[11] Bhattacharya SC, Abdul SP. Low greenhouse gas biomass options for cooking in the developing countries. Biomass Bioenerg 2002;22(4):305–17.
[12] Jin YL, Ma X, Chen XN, Cheng YB, Baris E, Ezzati M, et al. Exposure to indoor air pollution from household energy use in rural China: the interactions of technology, behavior, and knowledge in health risk management. Soc Sci Med 2006;62(12):3161–76.
[13] Kanagawa M, Nakata T. Analysis of the energy access improvement and its socio-economic impacts in rural areas of developing countries. Ecol Econ 2007;62(2):319–29.
[14] Zhou CJ. Rural energy resources and its utilization in the central catchment area of Yalutsangpu River and its two tributaries of Tibet. Resour Sci 1991;5:35–9.
[15] Cai GT, Zhang L. Tibetan rural energy consumption and its environmental impact. Resour Dev Market 2006;22(3):238–44.
[16] Wei XH, Yang P, Wang YJ. Use of rural energy resources and eco-environmental degradation in Tibet. J Environ Sci 2004;16(6):1046–50.
[17] Zhong GH, Tian YF, Wang M. Soil fertility of croplands in major agricultural areas in Tibet. Acta Pedologica Sin 2005;42(6):1030–4.
[18] Zou XY, Dong GR, Li S, Dong YX, Yang P, Jin HL, et al. Desertification and its prevention and control strategy in Tibet. J Nat Disast 2003;12(1):17–24.
[19] Ci R. Current status and causes of land desertification in the catchment area of Yalutsangpu River and its two tributaries of Tibet—accompanied by human factors. Res Tibet 2003;1:44–7.
[20] Zhao YZ, Zhang CL, Zou XY. Ecological security assessment and eco-environment construction of Xigaze prefecture on Tibetan plateau. Scientia Geographic Sin 2006;26(1):33–9.
[21] Shigatse Statistical Bureau. Statistic Yearbook of Shigatse; 2006.
[22] Wang GH. Analysis method on reducing emission of SO_2 and CO_2 by rural energy construction. Trans CSAE 1999;15(1):169–72.
[23] Srinivasan S. Positive externalities of domestic biogas initiatives: implications for financing. Renew Sustain Energy Rev 2008;12(5):1476–84.

[24] Liu G. Energy consumption patterns and its environmental effects in Tibet. Graduate university of Chinese Academy of Science Master Thesis; 2007.
[25] Luo TX, Li WH, Luo J. A comparative study on biological production of major vegetation types on the Tibetan Plateau. Acta Ecol Sin 1999;19(6):823–31.
[26] UNDP. Human Development Report 1995. New York: Oxford University Press; 1995.
[27] Qi XS, Zhang SP, Wang YZ. Advantages of the integrated pig-biogas-vegetable greenhouse system in North China. Ecol Eng 2005;24(3):175–83.

Tingting Feng is a PhD candidate of Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences in Beijing, China. Her major research is energy utilization and environmental effects concerning sustainable society development.

Shengkui Cheng is a professor of Institute of Geographic Sciences and Natural Resources Research. He focuses on the research about the sustainable utilization of natural resources and its eco-environment effects. He was awarded as elite of science and technology in Tibet for his continuous outstanding researches on releasing pressures of population-resources-environment in 1998.

Qingwen Min is a professor of the Institute of Geographic Sciences and Natural Resources Research, and his research focuses on protection of globally important agricultural heritage systems.

Wei Li is a PhD candidate of China Agricultural University, and his research area is land utilization and its eco-environment effects.